

THE LANL SOURCE GEOMETRY EXPERIMENT

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ABSTRACT

The Source Geometry Experiment was successfully conducted over the time period 17 April to 7 May 95. Recording in the mine was conducted 24 April to 4 May 95. Five single sources were instrumented that included four cylindrical charges at different burdens (distance from the free face) and a pseudo-spherical charge. Nine production shots conducted during the two week visit to the mine were also recorded. Included in these production shots were a number of explosions designed to primarily bulk (no cast) the overburden and a number which cast material into the mine pit. Instrumentation was divided into six primary types: (1) Near-source accelerometers were deployed at distances of approximately 20 to 300 m [14, three-component 25 g/volt accelerometers and 16, three-component 1 g/volt accelerometers]; (2) Linear array of velocity gauges to quantify wave propagation effects [4-11 three component strong motion velocity gauges]; (3) Far-field velocity gages deployed in an azimuthal array around the mine at ranges from 500 to 2500 m [8, three component velocity gauges]; (4) High speed film and multiple camera video designed to quantify the two and three dimensional affects around the explosions [2 high speed cameras and 3 Hi-8 video cameras]; (5) Velocity of detonation and detonation time measurements of selected explosions [2 VODR systems]; and (6) Pre and post shot laser survey. Any one shot had as many as 154 channels of data. Although the complete data set is still being assembled, quality checked and analyzed, it appears that nearly 2,000 channels of data were successfully recovered during the experiment. Preliminary analysis of the data illustrates the: (1) Significant spall accompanied both the cylindrical and spherical single sources; (2) Similarity of waveforms from the cylindrical and spherical single sources; (3) Strong variations in the body and surface wave generation from the nine production shot. Regional data from some of the sources recorded during this field experiment have been recovered and will be included in the analysis allowing results and interpretations from the close-in data to be extrapolated to regional distances.

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EXPERIMENTAL PURPOSE

The purpose of these experiments was focused on three primary issues. The first is directly linked to the efficiency of mining sources in the generation of both compressional and shear energy. This portion of the experiment produced data which can be used to develop a physical understanding of cylindrical explosive sources and the importance of the free-face which is failed in normal blasting practices. Single cylindrical sources, typical of the standard charges used in the multiple source production shots, were detonated at three different burdens. The first was that used in normal casting or fracturing shots. The second and third bridge the transition to a fully contained cylindrical source. The near-source and near-regional data spanning a number of azimuths gathered from these explosions will allow the quantification of energy coupling and the effect of the free-face in typical mining explosions.

The second issue to be addressed in this experimental series is the investigation of the charge shape, cylindrical in most mining applications, on the generation of seismic energy. A fully contained, pseudo-spherical, charge was designed, detonated and recorded using the same instrumentation array utilized in the cylindrical source study. This data will allow the cylindrical and spherical source geometry to be compared in a single geology. Extensive experience with spherical sources in a wide variety of geologies will allow this data to be extrapolated to other environments.

The final focus of this experimental study was the extension of the single, cylindrical source results to typical millisecond delay fired casting explosions. In this case multiple cylindrical explosions are detonated with millisecond delays between individual charges. The resulting waveforms are affected by the individual shot times as well as the interaction, possibly nonlinear, of the wavefield from each explosion. Nine, full production shots at the same mine and with the same cylindrical source configuration used in the single shot study were instrumented. Detonation times as well as velocity of detonation in the explosives for some of the holes in the explosive array were measured. This information along with the waveforms from the single cylindrical charges will allow a full assessment of both source interaction and timing effects.

In order to aid in the quantification of physical phenomena accompanying these explosions, multiple angle video and high speed photography accompanied the seismic measurements. This information will provide a quantification of two and three dimensional source processes and allow correlation with the resulting seismic measurements.

LOCATION OF THE EXPERIMENT

The mine is located outside of Terre Haute, Indiana. The mining operation is recovering coal from two seams, one at approximately 50 feet and the second near 100 feet. Explosions are used to remove this overburden which consists of a moderate to hard shale and lenticular sand units. Individual explosions in the casting shots range from 1000 to 4000 lbs. depending on whether 50 or 100 feet of overburden is removed in a single shot. Borehole diameters are 12 inches. Typical patterns consist of as many as 50 individual holes. Down hole delays are 700 milliseconds. These production casting or bulking shots are conducted approximately two out of every three days. There are homes and other structures near the mine requiring careful consideration of ground motions generated by the explosions. Aerial photography is completed by the mine on a frequent basis to assess progress. Figure 1 is an aerial view of the mine quantifying the size of the operation where we worked.

The areas where the experiments were conducted are highlighted in Figure 1. The source geometry experiments were completed in the east end of the pit where the first coal layer thins. Charge heights in this area of the pit are on the order of 100 feet with total explosive weight of 1800 to 3500 lbs. There is little surface topography in this portion of the mine and instrument installation was relatively easy, placing the surface installation in shallow holes that were backfilled with soil after leveling the instruments.

SHOT DESCRIPTIONS

Single Shots: Five single shot explosions were detonated during this experiment for the purpose of characterizing the single shot source and quantifying similarities and differences with a spherical explosion. As indicated in Figure 1, these explosions were conducted in the southeast corner of the mine. The characteristics of these five sources are summarized in Table 1.

Source Designation	Charge Size(lbs) ANFO/Emulsion	Bottom Hole depth (m)	Charge Height (m) 12" borehole	Overburden (m)
S1A	3381	30.5	23	7.5
S2	3248 464/hole	18.3 , 2.7 m between holes	7 x 3 m	15.3
S3	3514	30.5	23	7.5
S4	1856	30.5	11.5	19
S5	2586	30.5	23	7.5

Table 1: Single Shot Characteristics

The emplacement borehole for each of the single sources is diagrammed in Figure 2. The variability in the charge sizes for the three full column cylinders (S1A, S3 and S5) reflect practical differences in drilling and loading the explosive emplacement holes. The first single borehole drilled and loaded (S1) did not detonate as a result of water and possible isolation of the detonator from the explosive charge in the hole and thus a second source S1A was drilled and fired slightly offset from the first.

The location and proximity of the individual charges to the free face of the mine pit of the five single charges (and Production Shot 9) are illustrated in Figure 3. S5 was drilled at the normal burden of approximately 10 m although a vertical hole was used where typical production shots are drilled at a 20° angle to match the slope of the vertical face in front of the charge. S3 is approximately 60 m behind S5 and S1A is 60 m further away. S4 is at the same burden as S3 but as noted in Table 1 is half the size with increased overburden.

The pseudo-spherical shot, S2, consisted of seven boreholes drilled in a hexagonal pattern with a charge in the center. This configuration results in 7 boreholes, each 2.7 m from the other. Each hole was filled with 3 m of explosive, ~494 lbs, intended to simulate a spherical explosive source taking advantage of typical drilling and explosive loading capabilities at the mine (Figure 2). The seven charges were simultaneously detonated and the detonation times were verified using NONEL tubing connected to the primer, brought to the surface and tied into a bow tie above each charge (shock propagation in the NONEL tubing is approximately 2000 m/s). High speed film of the shot is used to determine the time of detonation as represented by the surface flash of the NONEL tubing.

Production Shots: During the course of the experiment a total of 9 production shots were recorded. The first of the production shots began in the northwest part of the mine (Figure 1)

and then moved towards the single shot test area (Figure 3) culminating in Production Shot 9 which was conducted directly adjacent to S5. This sequence of production shots provided the opportunity to characterize variations in blasting practices across the mine and directly compare a production shot with the single shot results. Because of its proximity to the single shots, Production Shot 9 was the most heavily instrumented. Velocity of detonation measurements as well as NONEL tubing at the surface were used to quantify actual as opposed to design detonation times.

In the northwest part of the mine the coal that is being initially recovered is relatively shallow and charge boreholes are less than 50 feet deep. The production shots in this area of the mine are designed to primarily bulk the material with little or no cast. As one moves to the southeast, the coal that is recovered is at approximately 100 feet; therefore, the charge holes are deeper and the individual explosions in each shot are larger. The explosions in this region of the mine are designed to cast material into the pit. Table 2 characterizes the 9 production shots.

SHOT	DESCRIP-TION	DAY	DATE	TIME	CHARGE
Prod1	6x6 (1000 lbs/hole)	114	24 April 95	20:35	~36,000 lbs, No Cast
Prod2	6x6 (1000 lbs/hole)	115	25 April 95	19:36:09	~36,000 lbs, No Cast
Prod3	6x6 (1000 lbs/hole)	116	26 April 95	19:45:34	~36,000 lbs, No Cast
Prod4	6x6 (3000 lbs/hole)	118	28 April 95	19:24:32	~108,000 lbs, Cast
Prod5	6x6 (1000 lbs/hole)	118	28 April 95	19:27:12	~36,000 lbs, No Cast
Prod6	6x6 (3000 lbs/hole)	119	29 April 95	16:07:02	~108,000 lbs, Cast
Prod7	6x9 (3000 lbs/hole)	121	1 May 95	19:33:49	~162,000 lbs, Cast
Prod8	6x6 (3000 lbs/hole)	123	3 May 95	21:32:39	~99,000 lbs (three holes no fire), Cast
Prod9	6x4 (3000 lbs/hole)	124	4 May 95	16:00:47	~72,000 lbs (most diagnostic info on any production shot), Cast

Table 2: Single and Production Shot Characteristics

PRELIMINARY ANALYSIS

Analysis of a small portion of the data collected during the course of this experiment has been conducted to assess the quality and quantity of data. The analysis has focused on the far-field seismic data. Figure 4 compares the whole record spectra from the pseudo-spherical shot (Shot 2) and the two cylindrical shots with maximum burden (Shot 1 and 3) (Figure 2 and 3,

Table 2) as recorded at Stations 4 and 6 (Figure 1). In addition to the signal spectra displayed in each figure, a pre-event noise estimate is also plotted indicating the good signal to noise ratios from 0.5/1 to nearly 100 Hz. The cylindrical and spherical sources produced identical vertical component waveforms at these two stations.

Shot 4 (Table 1) had approximately half the cylindrical charge of Shot 1 and had significantly more overburden (Figure 2). The detonation of this charge resulted in little permanent surface displacement unlike the other cylindrical charges. Comparison of the vertical spectra from the far-field seismic station 4 are reproduced in Figure 5. Within the bandwidth of the data (0.5-100 Hz) the smaller, deeper charge has reduced spectral amplitudes out to approximately 10 Hz. The two spectra appear to merge at the higher frequencies. Definitive conclusions on this coupling issue awaits analysis of the complete data set.

Shot 5 (Table 1 and 2) was detonated at the standard burden from the free face (Figure 3). This charge was drilled with a straight borehole rather than the typical 20° slant hole typically used by the mine. There was only a small amount of degradation of the free face by the explosion. There was no formation of a retarc as observed for Shots 1 and 3. There were, however, a number of large cracks parallel to the free face that opened as a result of the explosion indicating the degree of interaction with the free face. The vertical velocity spectra from this shot and one of the fully contained cylindrical shots (Shot 1) are given in Figure 6. There is little difference between the two records except a decrease in high frequency energy (above 4-5 Hz) for the shot at the free face.

It is critical to understand propagation path effects in attempting to assess source signatures on seismograms. Figure 7 is a comparison plot of the vertical velocity spectra at all far-field stations (Figure 1) from Shot 5. There is more than an order of magnitude difference in spectral levels as well as significant interference hole differences resulting from the propagation paths to each of these stations. This figure illustrates the need to conduct single shots in the experimental program in order to quantify these propagation path differences.

Vertical velocity spectra (far-field Station 4) from the single shot at the free face (Shot 5) and Production Shot 8 and 9 that are on either side of the single shot are reproduced in Figure 8. Spectral scalloping from the two production shots is observed closely spaced in frequency relative to the single shot result which is dominated by propagation path effects. This data will be used to assess the effect of timing variations on the resulting seismograms and to determine coupling differences observed at smaller frequencies resulting from the interaction of the multiple sources.

Production shots in this mine are used to both cast material and to bulk material depending on the needs of the mining operation. Production Shot 4 was a typical cast shot which was followed within minutes by a bulking shot, Production Shot 5. Production Shot 5 was detonated directly behind Production Shot 4 and thus the differences in propagation paths from these two shots to the far-field stations was minimal. Figure 9 compares the vertical velocity spectra from these two shots at Station 4. There is as much as a factor of 5 difference in the amplitudes from these two explosions. Interpretation of this data utilizing the accompanying loading and shooting data will provide the opportunity to assess variations in seismic signals that might be expected from a single mine.

CONCLUSIONS AND PLANS

The LANL Source Geometry Experiment was successfully carried out over the time period of 24 April through 4 May 95 excluding travel and deployment. A great variety of data types that

are intended to give a complete characterization of the seismic sources for these explosions were collected. This data included near-source acceleration, strong motion velocity, far-field velocity, regional seismic, velocity of detonation, high speed film, digital video, still photography, refraction and pre and post shot surveys. This experiment could have only been conducted with the close cooperation of industry and the hard work of the people pictured in this report.

Preliminary analysis indicates that the cylindrical source configuration typical of the mining community generates significant spall in the near-source region. Quantification of this process with the high speed film, digital video and spall zone acceleration measurements will allow us to assess its contribution to the seismic source function. Strong spall was observed from the cylindrical and the spherical sources.

Comparisons of far-field vertical velocity spectra indicates little or no difference between the fully burdened spherical and cylindrical sources (S1,S2,S3). These empirical results indicate that there are little differences in the coupling of compressional energy from these different source geometries. They also indicate that a well contained cylindrical charge or charges may be useful for calibrating a site. The resulting seismograms from the well contained cylindrical charge could produce compressional signals like that expected from a contained spherical explosion. Analysis of the horizontal motions will allow an assessment of the shear energy from these different source types and thus a complete assessment of the similarities and differences of cylindrical and spherical sources.

Subtle yield effects were observed in comparing the large and small cylindrical sources (S1 and S4). The effect of the free-face on the waveform may be dominant at high frequencies based on the comparison of the normal burden shot S5 and S1.

Comparison of the seismograms recorded from the nine production shots conducted during the deployment indicates a great deal of variability in amplitudes as well as relative body and surface wave contribution. Quantification of these differences will include an analysis of source differences (charge size and timing) as well as propagation path effects. The variability in the seismograms from a single shot (Figure 7) illustrates the importance of conducting a single shot to calibrate propagation path effects in the mine prior to attempting to interpret source differences. Significant source differences are observed over and beyond these propagation path effects as indicated by the comparison of the cast and bulking production shots (Production Shot 4 and 5) recorded at the same station.

PARTICIPANTS

The success of this experiment was critically dependent upon the support of many individuals. Support at the Chinook Mine came from John W. Brown - manager of drilling and blasting for AMAX, Randy Connor - senior drilling and blasting manager at Chinook, John D. Smith - JDS Mining Consultants, John Wiegand - Vibronics, Inc, and Michael Curtis - El Dorado Chemical Company. University support has come from David P. Anderson and Xiaoning Yang at Southern Methodist University and Catherine T. Aimone-Martin from New Mexico Tech. Engineering and instrumentation support was provided by Keith Kahara, Keith Dalrymple and Roy Boyd of EG&G. LANL personnel included D. Craig Pearson, C. L. Edwards, Brian Stump and Diane Baker. A special thanks goes to Jerry Matthews, the mine manager at Chinook, for his support and hospitality.

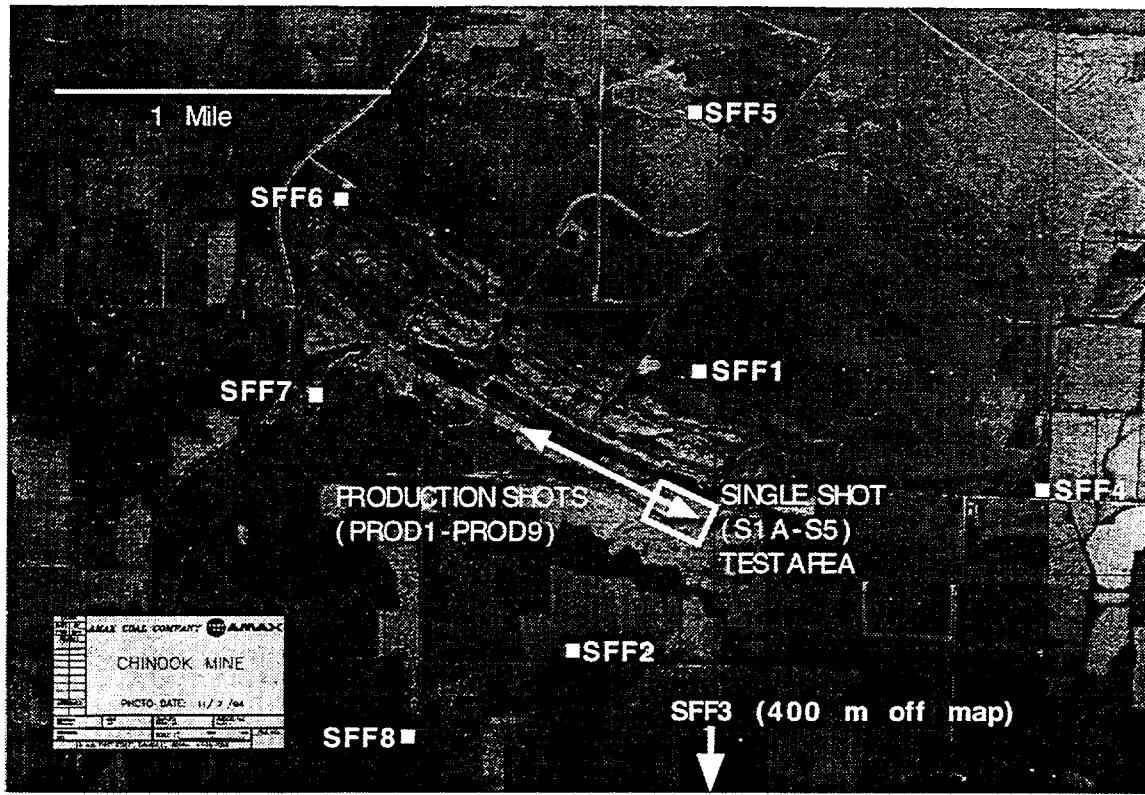


Figure 1. Aerial Photograph of the Chinook Mine with test areas and far-field seismic station locations.

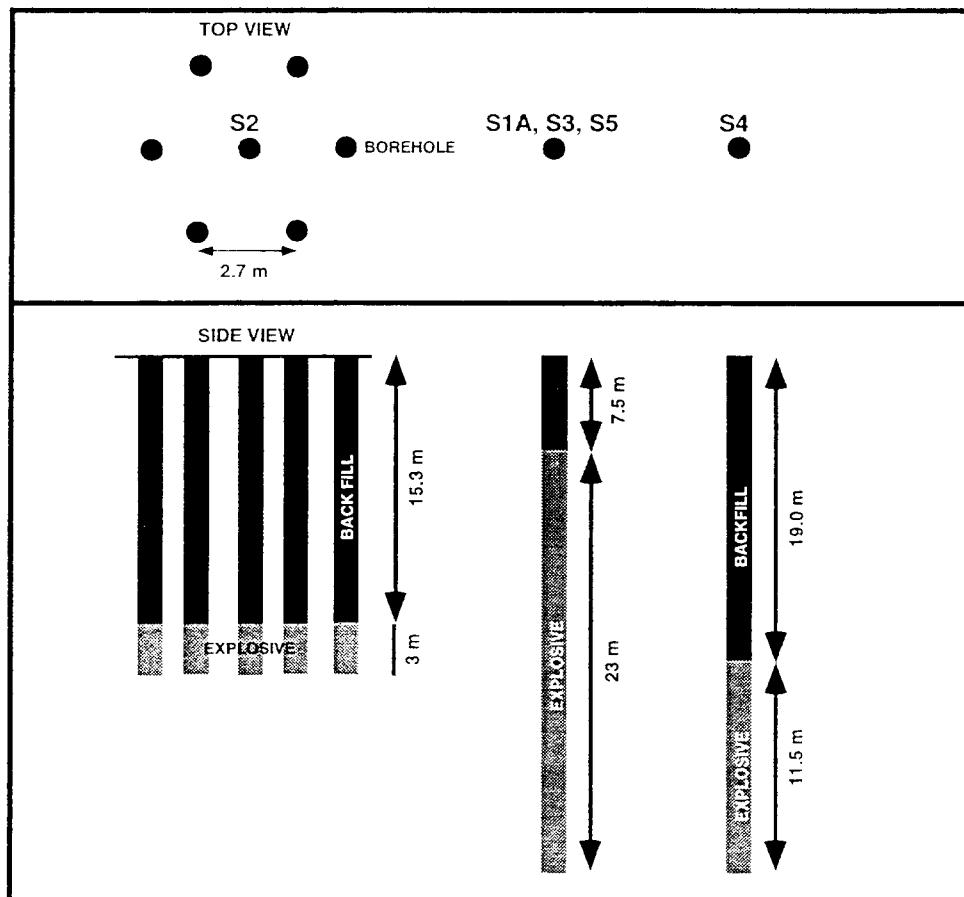


Fig 2. LANL Source Geometry Experiment, single shot configurations. Plan and side views of the three shot configurations used are shown.

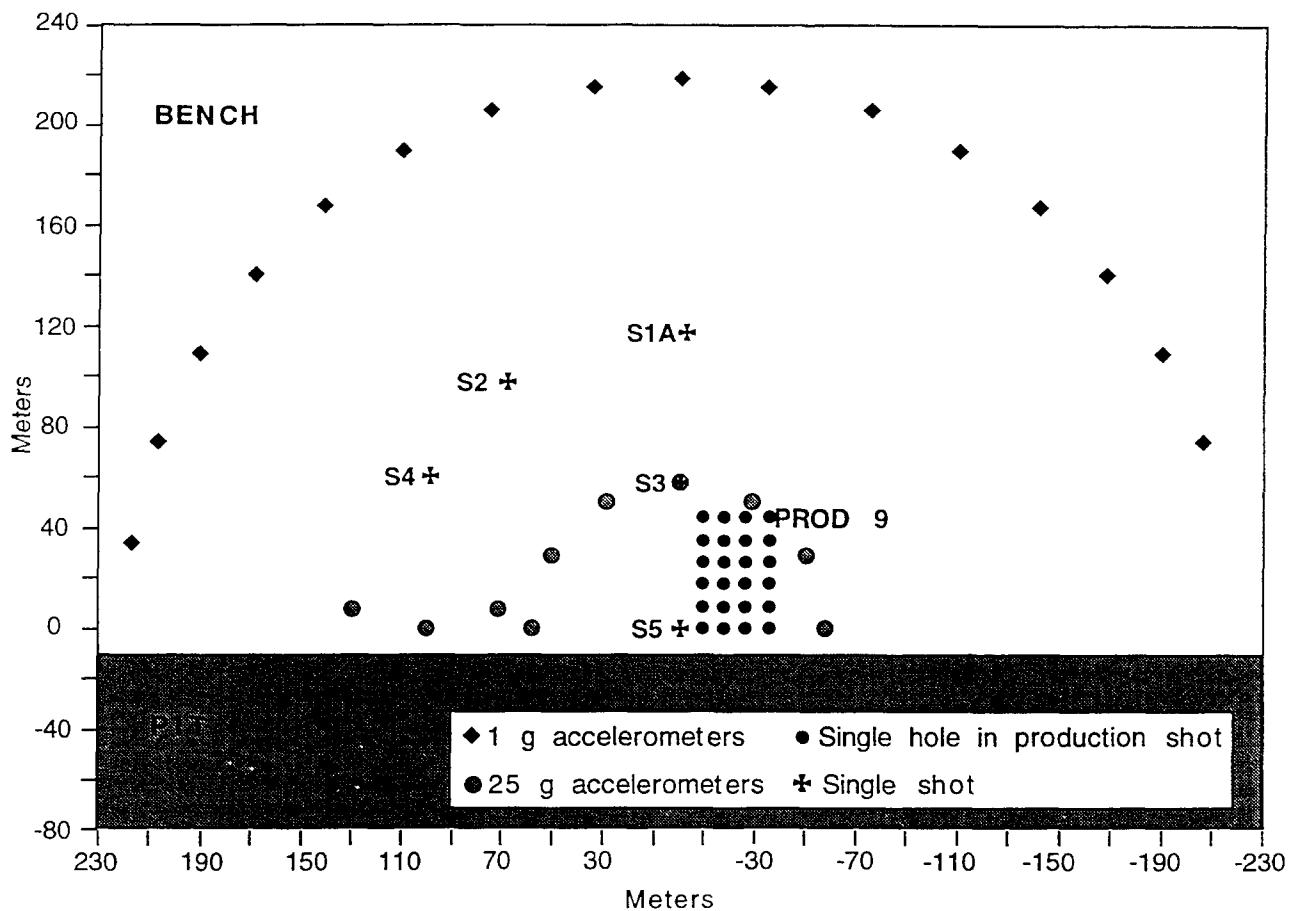


Fig 3: LANL Source Geometry Experiment, near source array deployment for shot S5.

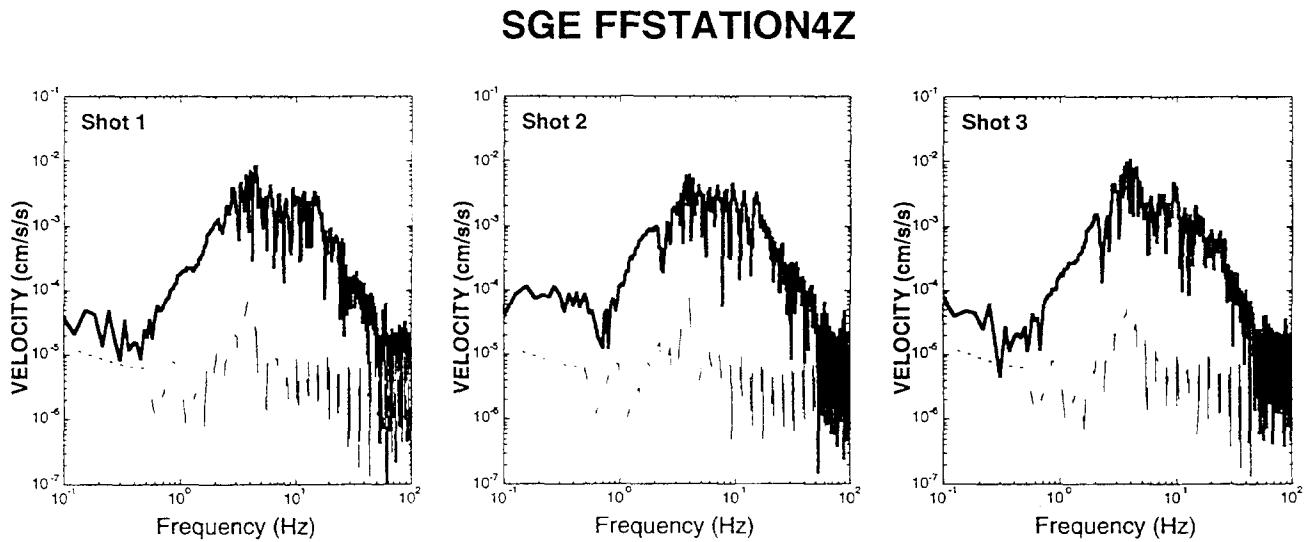


Fig 4: Vertical velocity spectra from Station 4 (Fig 2) for the two cylindrical charges (S1 & S3) and the spherical charge (S2).

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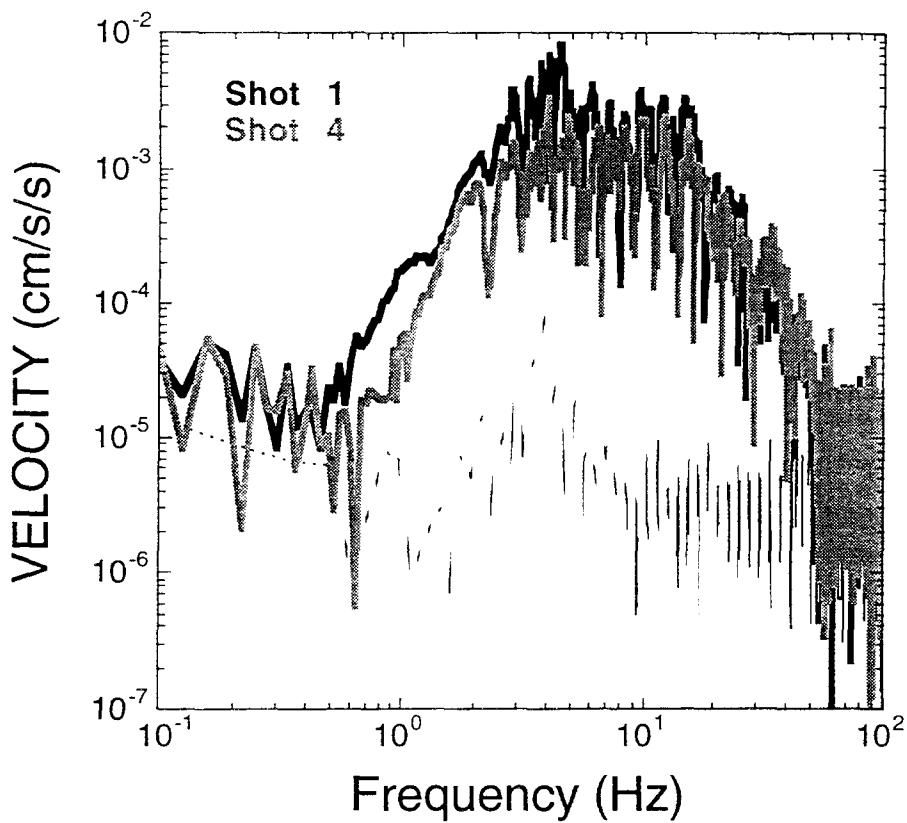


Fig 5: Vertical velocity spectra from Station 4 (Fig 2) for the full cylindrical charge (S1) and the half cylindrical charge (S4). The noise estimate is plotted as a dashed line.

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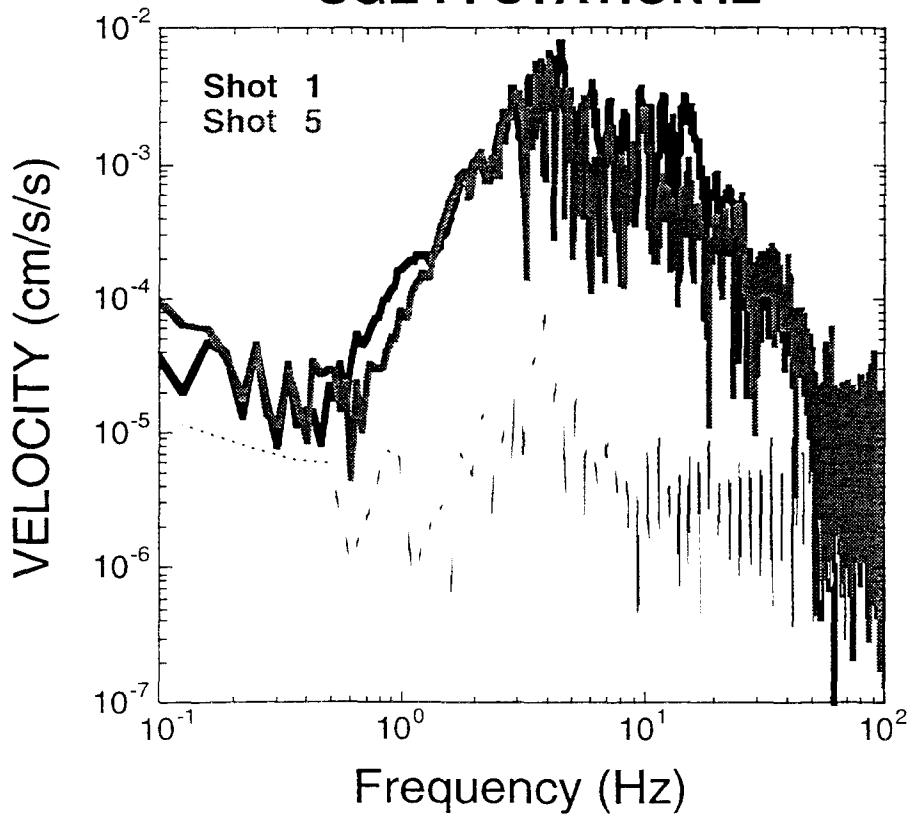


Fig 6: Vertical velocity spectra from Station 4 (Fig 2) for the fully burdened charge (S1) and the charge at the free face (S5). The noise estimate is plotted as a dashed line.

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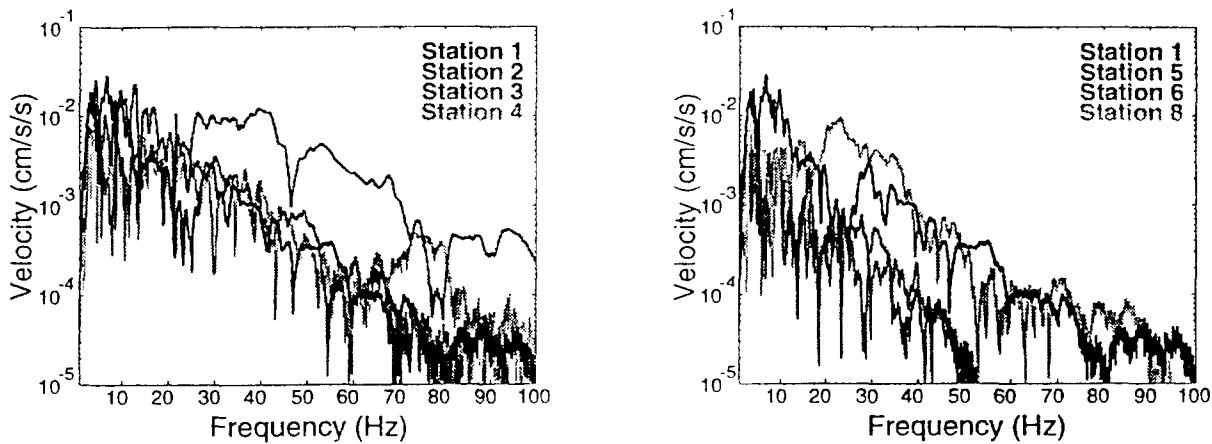


Fig 7: Vertical velocity spectra from all Far Field Stations for Shot 5 demonstrating the impact of propagation path effects. Plots are separated for clarity and the Station 1 spectrum is shown for reference in each plot.

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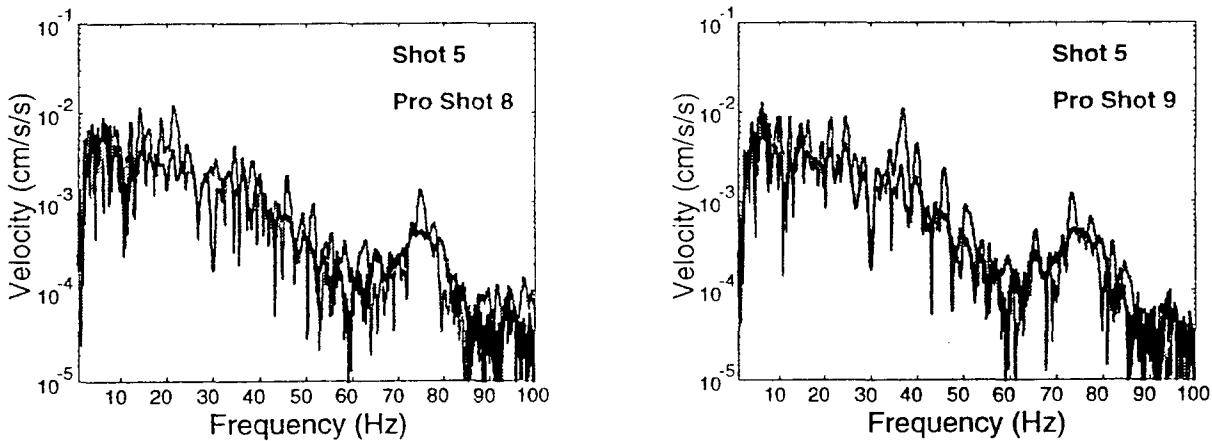


Fig 8: Vertical velocity spectra from Station 4 (Fig 2) for the single free face charge (S5) and the two near-by Production Shots 8 and 9. Plots are separated for clarity and the Shot 5 spectrum is shown for reference in each plot.

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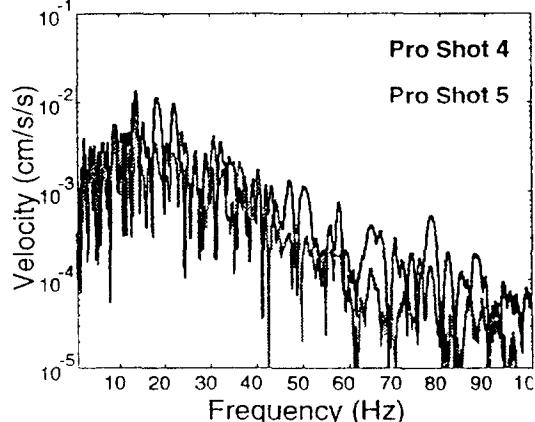


Fig 9: Vertical velocity spectra from Station 4 (Fig 2) for the two near-by explosions, Production Shot 4 which cast and Production Shot 5 which bulked.